

Elliptic and Hexadecapole flow of charged hadron in viscous hydrodynamics with Glauber and Color Glass Condensate initial conditions for Pb-Pb collision at $\sqrt{s_{NN}}=2.76$ TeV

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Abstract

The experimentally measured elliptic (v_2) and hexadecapole (v_4) flow of charged particles as a function of transverse momentum (p_T) at midrapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are compared with the relativistic viscous hydrodynamic model simulations. The simulations are carried out for two different initial energy density profiles obtained from (i) Glauber model, and (ii) Color Glass Condensate (CGC) model. Comparison to experimental data for 10-20% to 40-50% centrality, shows that a centrality dependent shear viscosity to entropy density (η/s) ratio with values ranging between 0.0 to 0.12 are needed to explain the v_2 data for simulations with the Glauber based initial condition. Whereas for the CGC based initial conditions a slightly higher value of η/s is preferred, around 0.08 to 0.16. From the comparison of the v_4 simulated results to the corresponding experimental measurements we observe that for the centralities 20-30% to 40-50% the η/s values lies between 0.0 to 0.12 for both the initial conditions studied. The η/s values obtained from our studies for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are compared to other studies which uses both transport and hydrodynamic approaches.

1. Introduction

One of the interesting aspects of the high energy heavy-ion collisions at the Large Hadron Collider (LHC) is that, a deconfined state of matter consisting of quarks and gluons, if produced in the collisions, exists for a sufficiently long duration so as to enable the study of its transport properties. The shear viscosity (η) is one of the transport coefficients that can be estimated by comparing the experimental data to the theoretical calculations based on either transport or hydrodynamic formulations. Particularly the experimental measurements of the azimuthal anisotropy of produced particles are compared to corresponding theoretical simulations to obtain an estimate of shear viscosity to entropy density ratio (η/s). Where the azimuthal anisotropy measurements in the experiments are characterized in terms of various coefficients of the Fourier expansion of the azimuthal distributions of produced particles relative to the reaction plane. The second coefficient, v_2 , is called as the elliptic flow and is the most widely used observable to extract the η/s value. Such approaches have been successfully applied to the experimental data for the Relativistic Heavy-ion collider (RHIC) energies. The extracted η/s values at RHIC are

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found to lie between $1 - 5 \times 1/4\pi[1, 2, 3, 4, 5, 6, 7]$. $\eta/s = 1/4\pi$ is the lower bound predicted by P. Kovtun et al. [8] (known as KSS limit) for strongly coupled quantum fluids using the string theoretical approaches.

At the LHC energies for Pb-Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV one expects the initial temperature attained in the collisions to be higher compared to that at RHIC for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Hence it would be interesting to find out the value of η/s for the QCD matter produced at a higher temperature at LHC compared to RHIC. The estimates so far carried out based on both transport theory [9, 10] and viscous hydrodynamic simulations [11, 12, 13, 14] have shown that the values of η/s at LHC energies are similar to those obtained at RHIC. The hydrodynamic approaches used included 2+1D simulations with smooth Glauber based initial conditions and 3+1D simulations with fluctuating initial conditions. These approaches mostly concentrated on explaining the measured v_2 for certain collision centrality classes. One of the dominant source of uncertainties in such estimates is the lack of complete knowledge of the initial conditions in the heavy-ion collisions. In this paper, we discuss results from a 2+1D smooth viscous hydrodynamic simulations with two different initial conditions, one based on Glauber model and other based on CGC approach. These simulations are then compared to centrality dependence of experimentally measured v_2 as well as new data on hexadecapole flow (v_4) as a function of transverse momentum from ATLAS [15] and ALICE experiments [17] at LHC. Our estimated values of η/s based on simulations with two different initial conditions and two observables, v_2 and v_4 are then compared to other existing results in the literature.

The paper is organized as follows. In the next section we discuss the details of our 2+1D viscous hydrodynamic simulations. These includes the initial conditions, an equation of state based on the lattice QCD and hadron resonance gas, and the freeze-out criteria. In section 3 we present the comparison of our simulation results to the corresponding experimental data at midrapidity for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. These includes the centrality dependence of the charged particle pseudorapidity density ($dN_{ch}/d\eta$), $v_2(p_T)$, and $v_4(p_T)$. In section 4 we present the predictions for charged hadron p_T spectra from our simulations for various collision centralities in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In section 5 we compare our estimated η/s values to other calculations. Finally we summarize our work and present a brief outlook in the section 6.

2. 2+1D viscous hydrodynamic simulations

The hydrodynamic simulation results presented here are based on the second order causal Israel-Stewart formalism for the evolution of a viscous fluid using the 2+1D viscous hydrodynamic code “AZHYDRO-KOLKATA” [18, 19]. Shear viscosity is the only dissipative process considered in our present study. We assume a net-baryon free plasma is formed in Pb-Pb collisions at midrapidity at $\sqrt{s_{NN}} = 2.76$ TeV, which is supported by the value of anti-proton to proton ratio being close to unity [20]. The code solves the following energy-momentum conservation equation along with the relaxation equation for shear viscosity.

$$\partial_\mu T^{\mu\nu} = 0, \quad (1)$$

$$\begin{aligned} D\pi^{\mu\nu} &= -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\nabla^{<\mu}u^{\nu>}) \\ &- [u^\mu\pi^{\nu\lambda} + u^\nu\pi^{\mu\lambda}]Du_\lambda. \end{aligned} \quad (2)$$

Where $T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu} + \pi^{\mu\nu}$ is the energy-momentum tensor, ε , p , u , and $\pi^{\mu\nu}$ are the energy density, pressure, fluid velocity and shear tensor respectively. $D = u^\mu \partial_\mu$ is the convective time derivative, $\nabla^{<\mu} u^{>\nu} = \frac{1}{2}(\nabla^\mu u^\nu + \nabla^\nu u^\mu) - \frac{1}{3}(\partial_\mu u^\mu)(g^{\mu\nu} - u^\mu u^\nu)$ is a symmetric traceless tensor. η is the shear viscosity and τ_π is the corresponding relaxation time. Assuming boost-invariance, the equations are solved in (τ, x, y, η) coordinate system.

2.1. Initial conditions

The initial conditions used here includes the initial energy density profile in the transverse plane ($\varepsilon(x, y)$). The $\varepsilon(x, y)$ is obtained using two different models - Glauber and CGC, the initial time (τ_i), the transverse velocity profile ($v_x(x, y)$, $v_y(x, y)$), shear stresses in the transverse plane ($\pi^{\mu\nu}(x, y)$) at τ_i . The τ_i value is taken as 0.6 fm. The temperature independent η/s values which are used as an input to the viscous hydrodynamics simulation are considered to be 0, 0.08, 0.12, and 0.16.

The two component Glauber model based initial condition for the transverse energy density is constructed as follows. At an impact parameter \mathbf{b} for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, the transverse energy density is obtained as,

$$\varepsilon(\mathbf{b}, x, y) = \epsilon_0[(1 - x_h)\frac{N_{part}}{2}(\mathbf{b}, x, y) + x_h N_{coll}(\mathbf{b}, x, y)] \quad (3)$$

where $N_{part}(\mathbf{b}, x, y)$ and $N_{coll}(\mathbf{b}, x, y)$ are the transverse profile of participant numbers and binary collision numbers respectively. The ϵ_0 corresponds to the central energy density for $b = 0$ collision and does not depend on the impact parameter of the collision. The parameter x_h is the hard scattering fraction. Both ϵ_0 and x_h are fixed to reproduce the experimental charged hadron multiplicity density at midrapidity ($dN_{ch}/d\eta$) of 1601 ± 60 for the central 0-5% collisions [21] for each value of η/s . No further adjustment of the parameters are done for other collision centralities. The values of ϵ_0 for different values of η/s are shown in Table 1. The $N_{part}(\mathbf{b}, x, y)$ and $N_{coll}(\mathbf{b}, x, y)$ values are obtained using an optical Glauber model calculation [22]. The inelastic nucleon-nucleon cross section is taken as 72 mb.

Table 1: Values of ϵ_0 used in Glauber, CGC model and the normalization constant C used in CGC model for initial transverse energy density.

η/s	ϵ_0 (GeV/fm ³), Glauber	C (GeV/fm ^{1/3}) CGC	ϵ_0 (GeV/fm ³), CGC
0.0	112	0.033	77.7
0.08	98	0.030	70.6
0.12	88	0.027	63.5
0.16	78	0.024	56.5

The CGC based initial transverse energy density profile is obtained as follows. We follow references [23, 24] and consider that the initial energy density can be obtained from the gluon number density through the thermodynamic relation,

$$\varepsilon(\tau_i, \mathbf{x}_T, b) = C \times \left[\frac{dN_g}{d^2\mathbf{x}_T dY}(\mathbf{x}_T, b) \right]^{4/3}, \quad (4)$$

where $\frac{dN_g}{d^2\mathbf{x}_T dY}$ is the gluon number density evaluated at central rapidity $Y = 0$ and the overall normalization C is a free parameter. C is fixed to reproduce the experimentally measured charged

particle multiplicity density at midrapidity. The values of C used in the simulations for different input values of η/s and the corresponding central energy densities are given in Table 1. The details of the implementation of this approach can be found in Refs [1, 25, 26].

Finally the shear stresses $\pi^{\mu\nu}$ are initialized to their corresponding Navier-Stokes estimates for the boost invariant velocity profile, $\pi^{xx} = \pi^{yy} = 2\eta/3\tau_i$, and $\pi^{xy} = 0$ [27]. We have used $\tau_\pi = 3\eta/4p$ (where η and p are the shear viscous coefficient and pressure) in our simulation, which corresponds to the kinetic theory estimates of relaxation time for shear viscous stress for a relativistic Boltzmann gas [28]. The initial values of $v_x(x, y)$ and $v_y(x, y)$ are taken to be zero.

2.2. Equation of state

The equation of state used here is a combination of high temperature phase from the Lattice QCD result with cross-over transition at temperature $T_c = 175$ MeV [29] and the low temperature phase is modeled by hadronic resonance gas, containing all the resonances with $M_{res} \leq 2.5$ GeV [30]. Entropy density (s) of the two phases are joined at $T = T_c = 175$ MeV by a smooth step like function. The thermodynamic variables pressure (p), energy density (ε), etc. are then calculated by using the standard thermodynamic relations.

$$p(T) = \int_0^T s(T') dT' \quad (5)$$

$$\varepsilon(T) = Ts(T) - p(T). \quad (6)$$

2.3. Freeze-out condition

We use the Cooper-Frey algorithm at the freezeout to calculate invariant yields of the hadrons [31]. The freezeout temperature which is a free parameter in the hydrodynamics simulation is taken as $T_f = 130$ MeV.

The freezeout distribution function in presence of viscous effects gets modified and can be approximated as [18]

$$f_{neq}(x, p) = f_{eq}(x, p)[1 + \phi(x, p)], \quad (7)$$

where $\phi(x, p) \ll 1$ is the corresponding deviation from the equilibrium distribution function $f_{eq}(x, p)$. The non-equilibrium correction $\phi(x, p)$ can be calculated in Grad's 14 moment method. According to which the viscous correction terms up to a quadratic function of the four momentum p^μ [32, 33]. As only shear stresses are considered, $\phi(x, p)$ has the following form

$$\phi(x, p) = \varepsilon_{\mu\nu} p^\mu p^\nu, \quad (8)$$

where

$$\varepsilon_{\mu\nu} = \frac{1}{2(\varepsilon + p)T^2} \pi_{\mu\nu}. \quad (9)$$

The correction factor thus increases with increasing values of shear stress $\pi_{\mu\nu}$ at freezeout. The correction term also depends on the particle momentum. The Cooper-Frey formula [31] for a non equilibrium system is

$$\frac{dN}{d^2p_T dy} = \frac{g}{(2\pi)^3} \int d\Sigma_\mu p^\mu f_{neq}(p^\mu u_\mu, T),$$

where g is the degeneracy of the particle considered and $d\Sigma_\mu$ is the normal to the elemental freeze-out hypersurface.

Table 2: Comparison of experimentally measured $dN_{ch}/d\eta$ at midrapidity for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for various collision centrality [21] to those obtained from a 2+1D viscous hydrodynamic simulations with Glauber and CGC based initial conditions.

% cross section	$dN_{ch}/d\eta$				
	Experiment	Glauber			
		$\eta/s = 0.0$	$\eta/s = 0.08$	$\eta/s = 0.12$	$\eta/s = 0.16$
0-5	1601 ± 60	1569	1572	1567	1565
10-20	966 ± 37	959	968	966	967
20-30	649 ± 23	637	647	649	651
30-40	426 ± 15	414	424	427	428
40-50	261 ± 9	248	256	260	260
% cross section	CGC				
	Experiment	$\eta/s = 0.0$	$\eta/s = 0.08$	$\eta/s = 0.12$	$\eta/s = 0.16$
0-5	1601 ± 60	1577	1629	1623	1626
10-20	966 ± 37	974	981	985	988
20-30	649 ± 23	640	666	668	670
30-40	426 ± 15	424	443	446	447
40-50	261 ± 9	259	274	276	276

3. Comparison to experimental data

The experimental data used for comparison to the simulated results are from the ALICE and ATLAS experiments at LHC. The observables are charged hadron multiplicity density ($dN_{ch}/d\eta$) at midrapidity [21], elliptic flow [15], and hexadecapole flow [17] as a function of p_T measured at midrapidity for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. All results are for collision centrality 10-20%, 20-30%, 30-40%, and 40-50%. For charged hadron yields we also present results for 0-5% collision centrality. This centrality is used to fix the initial energy density parameter in our simulations.

The $v_2(p_T)$ data is from the ATLAS experiment [15] and are obtained using the formula $v_2 = \langle \cos(2(\phi - \Psi_2)) \rangle$ after correction of the event plane resolution. Where ϕ is the azimuthal angle of the charged hadrons measured within $|\eta| < 1$ and Ψ_2 is the second order event plane constructed using a forward calorimeter detector in $3.2 < \eta < 4.9$. The rapidity gap between the detectors used to measure the v_2 and Ψ_2 ensures absence of significant $\Delta\eta$ dependent non-flow correlations, which are also absent in our hydrodynamic simulations. Ψ_2 is zero, i.e, the impact parameter vector 'b' is along x axis.

The $v_4(p_T)$ data is from the ALICE experiment [17] and are obtained using the formula $v_4 = \langle \cos(4(\phi - \Psi_4)) \rangle$ after correction of the event plane resolution. Where ϕ is the azimuthal angle of the charged hadrons measured within $|\eta| < 0.8$ and Ψ_4 is the fourth order event plane constructed using two scintillator arrays of detectors covering $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$. Like $v_2(p_T)$, the rapidity gap between the detectors used to measure the v_4 and Ψ_4 ensures absence of significant $\Delta\eta$ dependent non-flow correlations, which are also absent in our hydrodynamic simulations. Ψ_4 is zero for our simulation and impact parameter 'b' is along x axis.

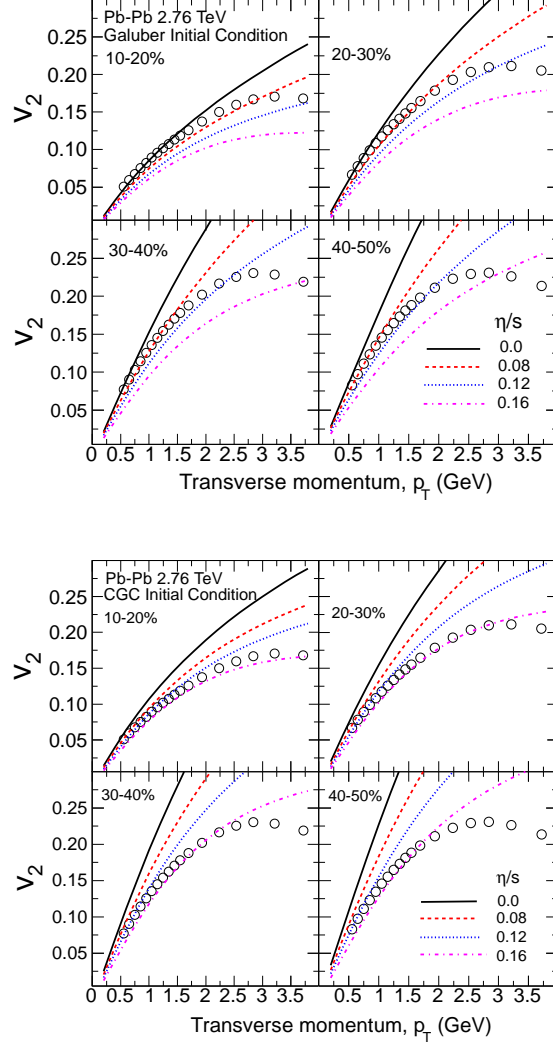


Figure 1: (Color online) Elliptic flow of charged hadrons as a function of transverse momentum at midrapidity for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The open circles corresponds to experimental data measured by the ATLAS collaboration [15]. The lines represent results from a 2+1D relativistic viscous hydrodynamic model with a Glauber based (upper panel) and CGC based (lower panel) initial transverse energy density profile and different η/s values.

3.1. Charged particle pseudorapidity density

The initial energy density profiles are fixed in the simulations by matching the experimental measured $dN_{ch}/d\eta$ for only 0-5% central Pb-Pb collisions at midrapidity for $\sqrt{s_{NN}} = 2.76$ TeV [21]. No adjustment of the parameters are done to match the $dN_{ch}/d\eta$ for the rest of the collision centralities 10-20%, 20-30%, 30-40%, and 40-50% studied in this paper. The table 2 shows the comparison between $dN_{ch}/d\eta$ at midrapidity as measured by ALICE for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV to our simulation results for various values of η/s for both Glauber and CGC based initial conditions. We observe for the collision centrality classes studied, there is good agreement between the experimental measurements and the simulated results for both the initial conditions.

3.2. Elliptic flow

Upper panel of Fig 1 shows the v_2 as a function of p_T for charged hadrons at midrapidity ($|\eta| < 1$) for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The results are shown for four different collision centralities (10-20%, 20-30%, 30-40%, and 40-50%). The open circles are the experimental data from the ATLAS collaboration [15]. The simulated results are from the 2+1D relativistic viscous hydrodynamic model with a Glauber based initial transverse energy density profile. The black solid, red dashed, blue dotted, and magenta dot-dashed lines corresponds to calculations with $\eta/s = 0.0, 0.08, 0.12$, and 0.16 respectively. The experimental data for 10-20% collision centrality is best described by ideal fluid ($\eta/s = 0.0$) simulation results for most of the p_T range for which comparison has been done. the experimental data for 40-50% collision centrality prefer a η/s between 0.08 and 0.12.

Lower panel of Fig. 1 shows the same results as in the upper panel but now the simulated results corresponds to 2+1D viscous hydrodynamic calculations with a CGC based initial transverse energy density profile. Comparison of the simulated results in the upper panel and lower panel for the same collision centrality shows that the $v_2(p_T)$ for CGC based initial condition is larger compared to corresponding results from Glauber based initial condition. This can be understood from the fact that CGC based initial condition leads to a higher value of momentum anisotropy compared to Glauber based initial condition [1]. We find from the comparison of experimental data to simulations based on CGC initial conditions that the $v_2(p_T)$ data for all the collision centralities studied are best explained for with η/s between 0.12-0.16. In contrast to Glauber based initial conditions we find the CGC based initial conditions prefer a slightly higher value of η/s for the LHC data.

3.3. Hexadecapole flow

Fig. 2 shows the hexadecapole flow (v_4) as a function of transverse momentum (p_T) for charged hadrons at midrapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The results are shown for four different collision centralities (10-20%, 20-30%, 30-40%, and 40-50%). The open circles are the experimental data from the ALICE collaboration [17]. The upper panel shows the simulated results for ideal and viscous fluid evolution using Glauber based initial condition, while the simulated results for the CGC based initial conditions are shown in the lower panel. We find that $v_4(p_T)$ from ideal hydrodynamic simulations with Glauber based initial conditions is smaller than the experimental data for 10-20% collision centrality and agrees with the experimental data at lower p_T for 20-30% collision centrality. For the more peripheral collisions of 30-40% and 40-50% centrality, the comparison of the simulated results to the experimental data shows that the preferred η/s lies between 0.0 and 0.08. A similar conclusion is also obtained from the comparison between simulated results with CGC based initial condition and experimental data.

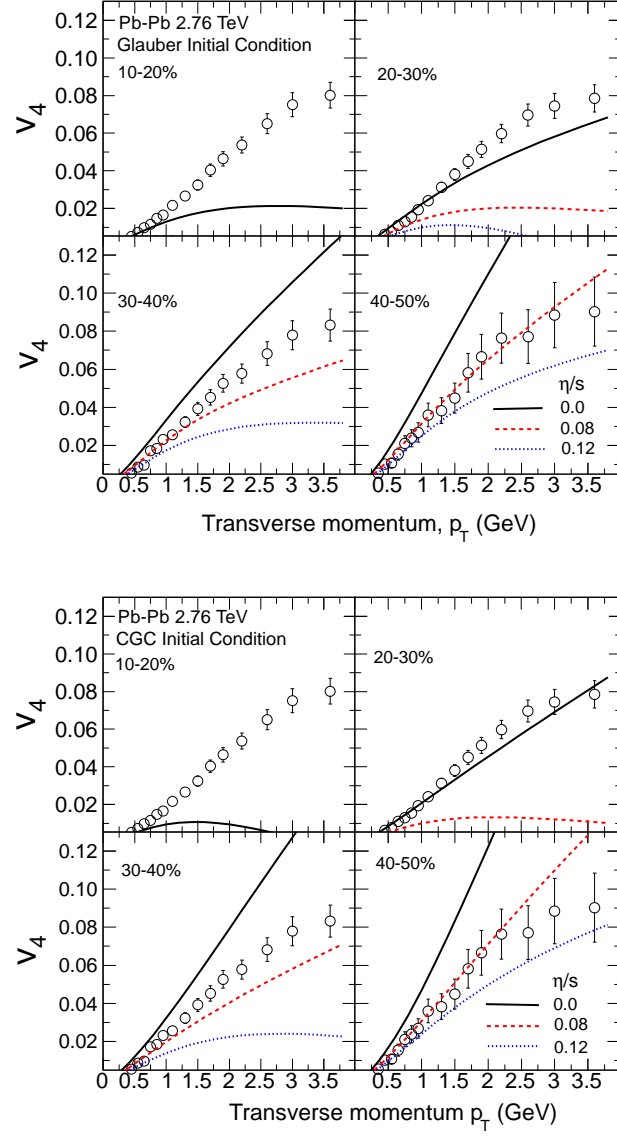


Figure 2: (Color online) Hexadecapole flow of charged hadrons as a function of transverse momentum at midrapidity for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The open circles corresponds to experimental data measured by the ALICE collaboration [17]. The lines represent results from a 2+1D relativistic viscous hydrodynamic model with both Glauber based (upper panel) and CGC based (lower panel) initial transverse energy density profile for different η/s values.

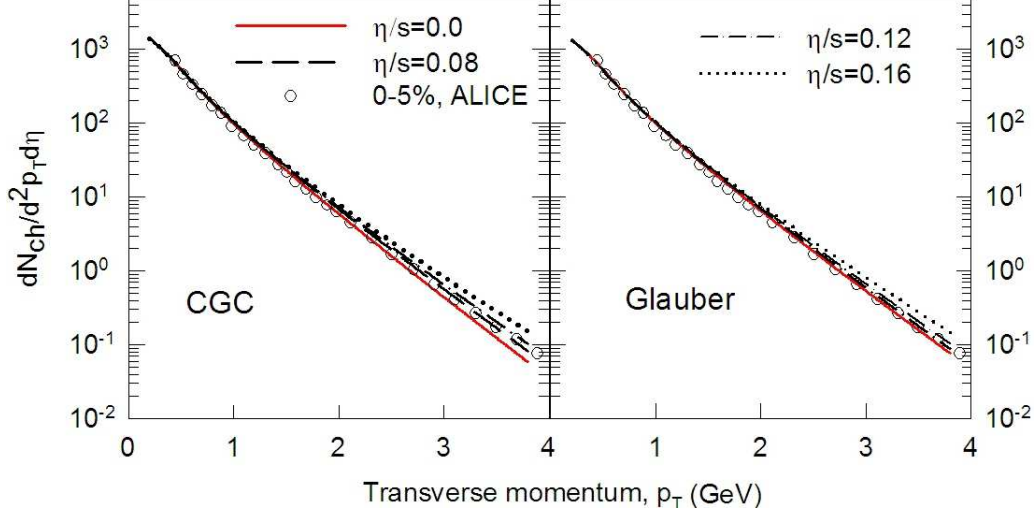


Figure 3: (Color online) Invariant yield of charged hadrons as a function of transverse momentum at midrapidity for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The open circles corresponds to experimental data for 0-5% centrality collision measured by the ALICE collaboration [16]. The lines represent results from a 2+1D relativistic viscous hydrodynamic model with a CGC based (left panel) and Glauber based (right panel) initial transverse energy density profile for different η/s values.

4. Simulated charged hadron transverse momentum spectra

We have compared our simulated results for charged hadron transverse momentum spectra with the available experimental data for 0-5% centrality Pb-Pb collision at LHC [16]. The comparison is shown in Fig 3. The left panel of Fig 3 is for CGC initial condition whereas the right panel of the same figure shows the result obtained for Glauber initial condition. We have fixed the initial energy density of the fluid and the freeze-out temperature by reproducing the experimental transverse momentum spectra of charged hadron for 0-5% collision centrality. So it will be illogical to extract viscosity by comparing simulation results to the experimentally measured transverse momentum spectra for 0-5% centrality.

Fig 4 shows the simulated invariant yield of charged hadrons as a function of transverse momentum at midrapidity for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for four different collision centralities (10-20%, 20-30%, 30-40%, and 40-50%). The open symbols corresponds to the simulated results from the 2+1D relativistic viscous hydrodynamic model with a Glauber based initial transverse energy density profile while the lines corresponds to the calculations with a CGC based initial condition. The black open circle (black solid line), red open square (red dashed), blue open triangle (blue dotted) and magenta diamond (magenta dash-dotted) symbols corresponds to simulations with $\eta/s = 0.0, 0.08, 0.12$, and 0.16 respectively. As we go from 10-20% collision centrality to 40-50% collision centrality for CGC based initial condition, spectra become more flatter than for Glauber initial condition. This means that the average transverse velocity at the freeze-out which determines the slope of the p_T spectra is slightly larger for the fluid evolution with Glauber than those corresponding to the CGC based initial conditions.

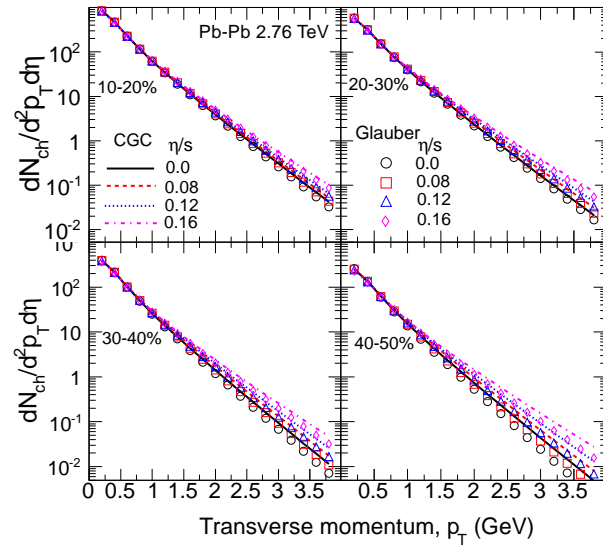


Figure 4: (Color online) Invariant yield of charged hadrons as a function of transverse momentum at midrapidity for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from a 2+1D relativistic viscous hydrodynamic model. The open symbols are for results obtained using Glauber based initial transverse energy density profile and different η/s values. The lines corresponds to calculations with CGC based initial transverse energy density profile. The results are shown for four different collision centralities 10-20%, 20-30%, 30-40%, and 40-50%.

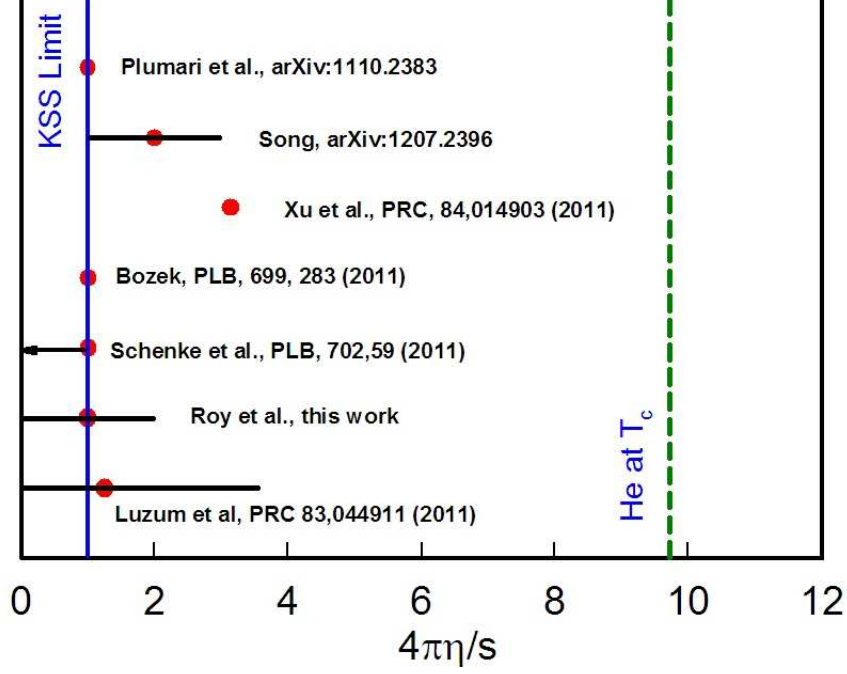


Figure 5: (Color online) Estimates of η/s using both transport and hydrodynamic approaches by different groups. The results are expressed in terms of multiples of the KSS limit.

5. Comparison of our estimate of η/s with other calculations

Fig 5 shows the comparison of the estimated η/s from the experimental data at LHC energies from various approaches to one obtained in the current work. Most of the results seems to indicate the value of $\eta/s < 4$ times the KSS limit. Two of the approaches shown in the figure are based on microscopic transport theory. The remaining are based on the macroscopic hydrodynamic approaches. J. Xu et al. [9], have estimated the specific shear viscosity using A Multi Phase Transport model (AMPT). They have explained the experimental data on charged particle pseudorapidity density per participating nucleon pair, $v_2(p_T)$ in 40-50% centrality, and the centrality dependence of v_2 for Pb-Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV. S. Plumari et al. [10], have used a parton cascade based approach with a temperature dependent $\eta/s(T)$ to simulate v_2 at LHC energies. They compare the simulated results to experimental measurements of $v_2(p_T)$ for 20-30% collision centrality Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. P. Bozek [11] has estimated the value of η/s by using a 2+1D viscous hydrodynamic model in which a Glauber based entropy density initialization was considered. In addition to shear viscosity a bulk viscosity to entropy density of 0.04 was also considered in the simulation. Further the freeze-out and resonance decay contributions were based on THERMINATOR event generator. M. Luzum [12] uses a 2+1D viscous hydrodynamic simulations to carry out shear viscous evolution starting from a smooth initial condition for LHC energies. B. Schenke et al. [13], uses a 3+1D viscous hydrodynamics with fluctuating initial conditions to explain the experimental data on $v_2(p_T)$ and p_T integrated v_2 for various collision centralities to estimate the value of η/s at LHC energies. H. Song [14] has

used a hybrid approach to explain the measured p_T integrated v_2 as well as p_T differential v_2 for various collision centrality in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The hybrid approach combines the macroscopic viscous hydrodynamic description for the QGP fluid with the microscopic hadron cascade model for the subsequent evolution of the hadronic stage.

6. SUMMARY

In summary, within the framework of Israel-Stewart's 2nd order hydrodynamics, we have simulated $\sqrt{s_{NN}}=2.76$ TeV Pb-Pb collisions at midrapidity. Two different initial conditions based on , (i) Glauber model and (ii) Color Glass Condensate (CGC), are used to model the initial transverse energy density distribution in Pb-Pb collision. The simulations are carried out for η/s values between 0.0 to 0.16, using a lattice + hadron resonance gas model based equation of state which has a cross over temperature for the quark-hadron transition at 175 MeV. The shear viscous corrections are considered both in the evolution equations and in the freeze-out distribution function.

We have compared our simulated results to the experimental data at midrapidity on the centrality dependence of $dN_{ch}/d\eta$, v_2 , and v_4 as a function of p_T of charged hadrons measured in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The comparisons have been done for the collision centrality classes of 10-20%, 20-30%, 30-40%, and 40-50%. We find there is nice agreement between the experimental measured $dN_{ch}/d\eta$ and the simulated results for both Glauber and CGC initial conditions. The $v_2(p_T)$ experimental data requires a slightly lower value of η/s for simulations with Glauber model initialization compared to the CGC based initial conditions. For a Glauber based initial condition the data prefers a η/s value between 0.0 to 0.12, while for CGC based initial condition it prefers a value between 0.08 to 0.16. The experimental data on $v_4(p_T)$ for the higher collision centralities are in general higher compared to results from ideal hydrodynamic simulations. For the more peripheral collisions of 30-40% and 40-50% centrality, the comparison of the simulated results to the experimental data shows that the preferred η/s lies between 0.0 and 0.08 for both Glauber and CGC based initial conditions.

The current work uses smooth initial conditions. A more realistic approach would be to use a fluctuating initial condition and carry out event-by-event hydrodynamics. This will enable us to study the odd flow harmonics v_3 along with the even harmonics v_2 and v_4 . The simultaneous description of all these experimentally measured flow harmonics in a viscous hydrodynamics framework will probably provide a better estimation of η/s at the LHC energies. We plan to consider some of these effects in the near future. The current results however agrees well with other estimates of η/s for the same experimental data. These estimates are based on both transport and hydrodynamic approaches. All results seems to indicate that the value of η/s for the QCD matter formed Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is between $1 - 4 \times 1/4\pi$ (the KSS limit). This value is very close to that obtained for QCD matter at RHIC energies ($\sqrt{s_{NN}} = 200$ GeV) [1, 2, 3, 4, 5, 6, 7].

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